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CHAPTER 2

BASIC DIELECTRIC THEORY OF CABLE

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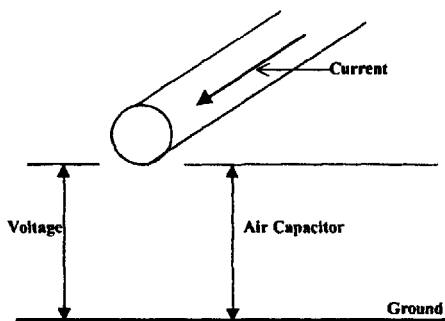
1. INTRODUCTION

Whether being used to convey electric power or signals, it is the purpose of a wire or cable to convey the electric current to the intended device or location. In order to accomplish this, a conductor is provided which is adequate to convey the electric current imposed. Equally important is the need to keep the current from flowing in unintended paths rather than the conductor provided. Insulation is provided to largely isolate the conductor from other paths or surfaces through which the current might flow. Therefore, it may be said that any conductor conveying electric signals or power is an insulated conductor.

2. AIR INSULATED CONDUCTORS

A metallic conductor suspended from insulating supports, surrounded by air, and carrying electric signals or power may be considered as the simplest case of an insulated conductor. It also presents an opportunity to easily visualize the parameters involved.

Figure 2-1
Location of Voltage and Current



In Figure 2-1, clearly the voltage is between the conductor and the ground [2-3, 2-4]. Also, because of the charge separation, there is a capacitor and a large resistance between conductor and ground. Finally, as long as ground is well

away from the conductor, the electric field lines leave the conductor as reasonably straight lines emanating from the center of the conductor. We know that all bend to ultimately terminate at ground.

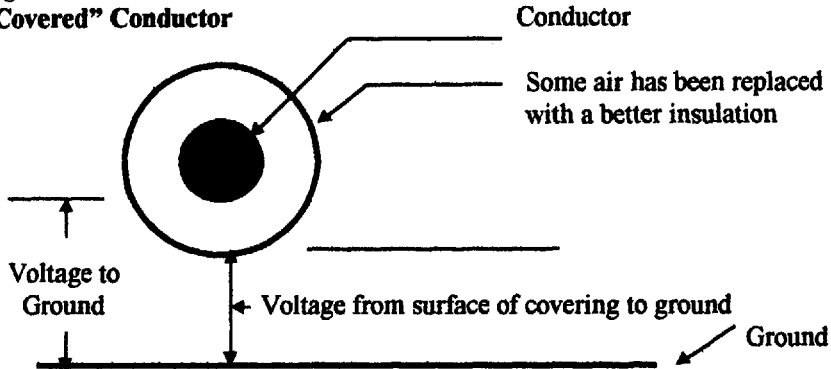
Air is not a very good insulating material since it has a lower voltage breakdown strength than many other insulating materials. It is low in cost if space is not a constraint. As the voltage between the conductor and ground is increased, a point is reached where the electric stress at the conductor exceeds the breakdown strength of air. At this point, the air literally breaks down producing a layer of ionized, conducting air surrounding the conductor. The term for this is corona (crown). It represents power loss and can cause interference to radio, TV, and other signals. It is not uncommon for this condition to appear at isolated spots where a rough burr appears on the conductor or at a connector. This is simply because the electric stress is locally increased by the sharpness of the irregularity or protrusion from the conductor. In air or other gasses, the effect of the ionized gas layer surrounding the conductor is to increase the electrical diameter of the conductor to a point where the air beyond the ionized boundary is no longer stressed to breakdown for the prevailing temperature, pressure, and humidity. The unlimited supply of fresh air and the conditions just mentioned, precludes the progression of the ionization of air all the way to ground. It is possible that the stress level is so high that an ionized channel can breach the entire gap from conductor to earth, but this generally requires a very high voltage source such as lightning.

3. INSULATING TO SAVE SPACE

Space is a common constraint that precludes the use of air as an insulator. Imagine the space requirements to wire a house or apartment using bare conductors on supports with air as the insulation. Let's consider the next step where some of the air surrounding the previous conductor is replaced with a better insulating material -- also known as a dielectric.

In Figure 2-2, we see that the voltage from conductor to ground is the same as before. A voltage divider has been created that is made up the impedance from the covering surface to ground. The distribution of voltage from conductor to the surface of the covering and from the covering surface to ground will be in proportion to these impedances. It is important to note that with ground relatively far away from the covered conductor, the majority of the voltage exists from the covering surface to ground. Putting this another way, the outer surface of the covering has a voltage that is within a few percent of the voltage on the conductor (95 to 97% is a common value).

Figure 2-2
"Covered" Conductor



The amount of current that can flow from an intact covering to ground in the event of contact is limited by the impedance of the covering. If the covering is made of an excellent insulation, the majority of the current will be due to capacitive charging current that can be released from the covering surface by the contacting object.

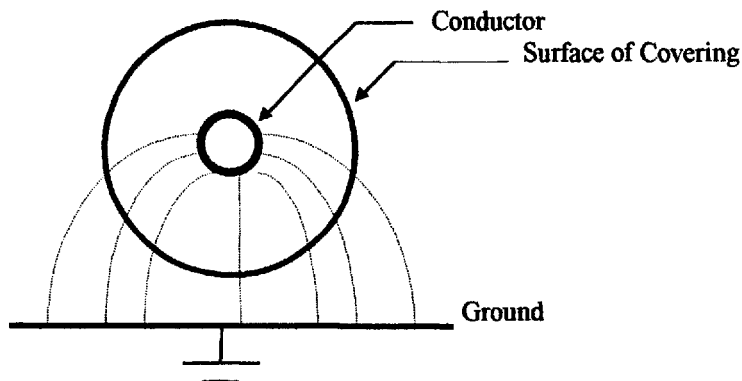
So little current is available at the covering surface from a low voltage covering (600 volts or less), that it is imperceptible. When this condition exists with some level of confidence, the "covering" is then considered to be "insulation" and suitable for continuous contact by a grounded surface as long as such contact does not result in chemical or thermal degradation. The question arises as to what is considered to be low voltage. The voltage rating of insulated cables is based on the phase-to-phase voltage. Low voltage is generally considered to be less than 600 volts phase-to-phase. See Chapters 4 and 9 for additional information.

Because of the proximity and contact with other objects, the thickness of insulating materials used for low voltage cables is generally based on mechanical requirements rather than electrical. The surrounding environment, the need for special properties such as sunlight, or flame resistance, and rigors of installation often make it difficult for a single material satisfy all related requirements. Designs involving two or more layers are commonly used in low voltage cable designs.

4. AS THE VOLTAGE RISES

Return to the metallic conductor that is covered with an insulating material and suspended in air. When the ground plane is brought close or touches the covering, the electric field lines become increasingly distorted.

Figure 2-3
Electric Field Lines Bend to Terminate at Ground Plane



In Figure 2-3, we see considerable bending of the electric field lines. Recognizing that equipotential lines are perpendicular to the field lines, the bending results in potential difference on the covering surface. At low voltages, the effect is negligible. As the voltage increases, the point is reached where the potential gradients are sufficient to cause current to flow across the surface of the covering. This is commonly known as "tracking." Even though the currents are small, the high surface resistance causes heating to take place which ultimately damages the covering. If this condition is allowed to continue, eventually the erosion may progress to failure.

It is important to note that the utilization of spacer cable systems and heavy walled tree wires depend on this ability of the covering to reduce current flow to a minimum. When sustained contact with branches, limbs, or other objects occurs, damage may result -- hence such contacts may not be left permanently.

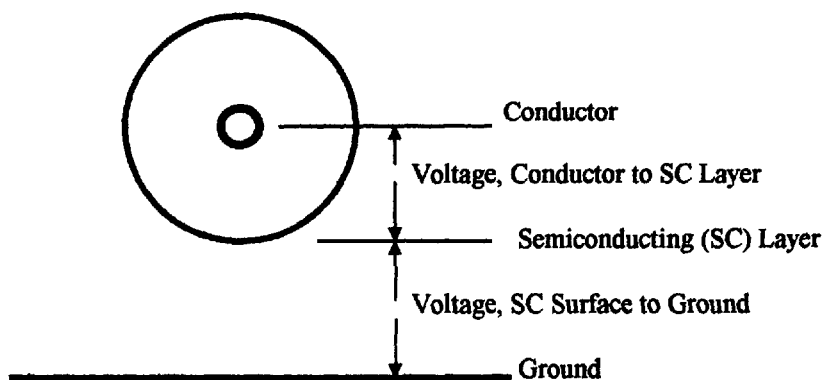
At first, it might be thought that the solution is to continue to add insulating covering thickness as the operating voltage increases. Cost and complications involved in overcoming this difficulty would make this a desirable first choice. Unfortunately, surface erosion and personnel hazards are not linear functions of voltage versus thickness and this approach becomes impractical.

4.1 The Insulation Shield

In order to make permanent ground contact possible, a semiconducting or resistive layer may be placed over the insulation surface. This material forces the

ending of the field lines to occur in the semiconducting layer. This layer creates some complications, however.

Figure 2-4



In Figure 2-4, it is clear that a capacitor has been created from the conductor to the surface of semiconducting layer. A great deal of charge can be contained in this capacitor. This charging current must be controlled so that a path to ground is not established along the surface of the semiconducting layer. This path can lead to burning and ultimate failure of that layer. Accidental human contact would be a very serious alternative. It is clearly necessary to provide a continuous contact with ground that provides an adequate path to drain the capacitive charging current to ground without damage to the cable. This is done by adding a metallic path in contact with the semiconducting shield.

Once a metallic member has been added to the shield system, there is simply no way to avoid its presence under ground fault conditions. This must be considered by either providing adequate conductive capacity in the shield to handle the fault currents or to provide supplemental means to accomplish this. This is a critical factor in cable design.

Electric utility cables have fault current requirements that are sufficiently large that it is common to provide for a neutral in the design of the metallic shield. These cables have become known as Underground Residential Distribution (URD) and Underground Distribution (UD) style cables. It is important that the functions of the metallic shield system are understood since many serious errors and accidents have occurred because the functions were misunderstood. The maximum stress occurs at the conductor.

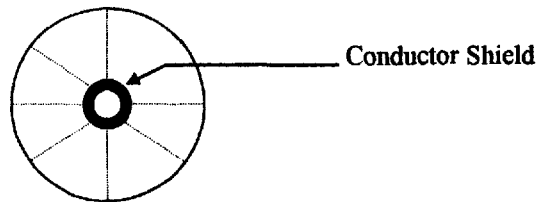
4.2 A Conductor Shield is Needed

The presence of an insulation shield creates another complication. The grounded insulation shield results in the entire voltage stress being placed across the insulation.

Just as in the case of the air insulated conductor, there is concern about exceeding maximum stress that the insulating layer can withstand. The problem is magnified by stranded conductors or burrs and scratches that may be present in both stranded and solid conductors.

Figure 2-5

A Conductor Shield is Added to Provide a Smooth Inner Electrode



In Figure 2-5, a semiconducting layer has been added over the conductor to smooth out any irregularities. This reduces the probability of protrusions into the insulating layer. Protrusions into the insulation or into the semiconducting layer increase the localized stress (stress enhancement) that may exceed the long term breakdown strength of the insulation. This is especially critical in the case of extruded dielectric insulations. Unlike air, there can be no fresh supply of insulation. Any damage will be progressive and lead to total breakdown of the insulating layer. There will be more discussion about “treeing” in Chapter 16.

4.3 Shielding Layer Requirements

There are certain requirements inherent in shielding layers to reduce stress enhancement. First, protrusions, whether by material smoothness or manufacturing, must be minimized. Such protrusions defeat the very purpose of a shield by enhancing electrical stress. The insulation shield layer has a further complication in that it is desirable to have it easily removable to facilitate splicing and terminating. This certainly is the case in the medium voltage (5 to 35 kV). At higher voltages, the inconveniences of a bonded

insulation shield can be tolerated to gain the additional probability of a smooth, void-free insulation-insulation shield interface for cable with a bonded shield.

4.4 Insulation Layer Requirements

At medium and higher voltages, it is critical that both the insulation and insulation-shield interfaces be contamination free. Contamination results in stress enhancement that can increase the probability of breakdown. Voids can do the same with the additional possibility of capacitive-resistive (CR) discharges in the gas-filled void as voltage gradients appear across the void. Such discharges can be destructive of the surrounding insulating material and lead to progressive deterioration and breakdown.

4.5 Jackets

In low voltage applications, jackets are commonly used to protect underlying layers from physical abuse, sunlight, flame or chemical attack. Chemical attack includes corrosion of underlying metallic layers for shielding and armoring. In multi-conductor designs, overall jackets are common for the same purposes. For medium and high voltage cables, jackets have been almost universally used throughout the history of cable designs. They are used for the same purposes as for low voltage cables with special emphasis on protecting underlying metallic components from corrosion. The only exceptions were paper-insulated, lead-covered cables and early URD/UD designs that were widely used by the electric utility industry. Both "experiments" were based on the assumption that lead, and subsequently copper wires, were not subject to significant corrosion. Both experiments resulted in elevated failure rates for these designs. Jackets are presently used for these designs.

5. TERMINOLOGY [2-1]

To better understand the terminology that will be used throughout this book, a brief introduction of the terms follows.

5.1 Medium Voltage Shielded Cables

Medium voltage (5 kV to 46 kV) shielded cable appears to be a relatively simple electrical machine. It does electrical work but there are no parts that move, at least no discernible movement to the naked eye. Do not be misled. This cable is a sophisticated electrical machine, even though it looks commonplace. To know why it is constructed the way it is, let us first look at a

relatively simple cable, a low voltage non-shielded cable. For simplicity, we shall confine this discussion to single conductor cable.

5.1.1 Basic Components of Non-Shielded Power Cable. There are only two components in this cable, a conductor and its overlying insulation.

5.1.2 Conductor. The conductor may be solid or stranded and its metal usually is either copper or aluminum. An attempt to use sodium was short-lived. The strand can be concentric, compressed, compacted, segmental, or annular to achieve desired properties of flexibility, diameter, and current density.

Assuming the same cross-sectional area of conductor, there is a difference in diameters between solid and the various stranded conductors. This diameter differential is an important consideration in selecting methods to effect joints, terminations, and fill of conduits.

5.1.3 Electrical Insulation (Dielectric). This provides sufficient separation between the conductor and the nearest electrical ground to preclude dielectric failure. For low voltage cables, (2,000 volts and below), the required thickness of insulation to physically protect the conductor is more than adequate for required dielectric strength.

5.1.4 Dielectric Field. The conductor and the insulation are visible to the unaided eye. However, there is a third component in this cable. It is invisible to the unaided eye. This third component is what contributes to sophistication of the electrical machine known as cable. Alternating current fields will be discussed, not direct current

In all cables, regardless of their kV ratings, there exists a dielectric field whenever the conductor is energized. This dielectric field can be visualized by lines of electrostatic flux and equi-potentials. Electrostatic flux lines represent the boundaries of dielectric flux between electrodes having different electrical potentials. Equi-potential lines represent points of equal potential difference between electrodes having different electrical potentials. They represent the radial voltage stresses in the insulation and their relative spacing indicates the magnitude of the voltage stress. The closer the lines, the higher the stress. See Figures 2-1, 2-2, and 2-3.

If the cable is at an infinite distance from electrical ground (ideal situation), there will be no distortion of this dielectric field. The electrostatic flux lines will radiate between the conductor and the surface of the cable insulation with symmetrical spacing between them. The lines of equi-potential will be

concentric with relation to the conductor and the surface of the cable insulation. However, in actual practice this ideal situation does not exist.

In actual practice, the surface of the cable insulation is expected to be in contact with an electrical ground. This actual operating condition creates distortion in the dielectric field. The lines of electrostatic flux are crowded in the area of the insulation closest to ground.

The lines of equi-potential are eccentric with respect to the conductor and the surface of the cable insulation. This situation is tolerated if the dielectric strength of the cable insulation is sufficient to resist the flow of electrons (lines of electrostatic flux), and the surface discharges and internal voltage stresses that are due to concentrated voltage gradients (stresses) that are represented by lines of equi-potential. Low voltage, non-shielded cables are designed to withstand this condition. Service performance of non-shielded cables is generally considered acceptable. Thus one may ask "Why not extrapolate non-shielded cable wall thickness for increasing voltages?" There are very practical limits, economics being paramount, to such an approach.

5.1.5 Extrapolation of 600 Volt and 5 kV Cable Walls. If we use the same volts per mil wall thickness of 600 volt cable to determine higher voltage walls, we achieve a wall of at least 4.6 inches (117 mm) for a 35 kV cable.

A similar approach using 5 kV cable voltage stress as the basis for extrapolation provides at least a 0.63 inch (16 mm) wall for a 35 kV cable.

5.1.6 Summary of Limitation. It is apparent that the bulk dimensions created by extrapolation of non-shielded cable walls are unacceptable. To overcome this situation of bulk dimensions, generally shielded cable is used.

5.2 Basic Components of a Shielded Power Cable

The essential additional component is shielding. However, where is it placed, what materials are used, and what does it do to the dielectric field? Let us start from the conductor again and move outward from the center of the cable.

5.2.1 Conductor. Nothing unusual as compared to a non-shielded cable.

5.2.2 Conductor Shield. A conducting material is placed over the conductor circumference to screen (shield) out irregularities of the conductor contours. The dielectric field will not be affected or "see" the shape of the outer strands

(or other conductor contours) due to the presence of the conductor shield (screen).

5.2.3 Electrical Insulation (Dielectric). The differences between insulation for a non-shielded cable as compared to a shielded cable are in material, quality, cleanliness, and application. The thickness applied is primarily influenced by considerations of electrical stress (voltage gradients).

5.2.4 Insulation Shield. This is a two-part system, consisting of an auxiliary shield and a primary shield.

5.2.5 Auxiliary Shield. A conducting material that is placed over the outer diameter of the cable insulation. This material must be capable of conducting "leakage" current radially through its wall without creating an abnormal voltage drop.

5.2.6 Primary Shield. A metallic layer of tapes, wires, or a tube that is placed over the circumference of the underlying auxiliary shield. This must be capable of conducting the summation of "leakage" currents and carry them to the nearest ground without creation of an abnormal voltage drop.

5.2.7 Dielectric Field. A dielectric field, composed of electrostatic flux and equi-potential lines, exists when the conductor is energized. There is no distortion in this dielectric field because of the shielding of insulation and conductor. Electrostatic flux lines are symmetrically spaced and equi-potential lines are concentric. See Figure 2-3.

However, observe features not previously noted; the electrostatic flux and equi-potential lines are spaced closer together near the conductor shield as compared to their spacing near the insulation shield. This is why we are cognizant of maximum stresses at areas of minimum radii (and diameters). Insulation voids at the conductor shield are more critical than voids at the insulation shield. Also these lines are spaced closer together at the minimum diameter (or radii). This substantiates the maximum radial stress theory.

5.2.8 Insulation Thickness. The use of shielded cable permits using cables that are more economic to manufacture and install as compared to non-shielded cables that would require very heavy insulation thickness. Table 2-2 provides a comparison.

5.2.9 Jacket or Outer Coverings. Over the insulation shielding system, the cable contains components that provide environmental protection for the cable.

This can be extruded jacket (of synthetic material), metal sheath or wires, armoring, or a combination of these items.

6. REFERENCES

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[2-3] A. Clapp, C. C. Landinger, and W. A. Thue, "Design and Application of Aerial Systems Using Insulating and Covered Wire and Cable," *Proceedings of the 1996 IEEE/PES Transmission and Distribution Conference*, 96CH35968, Los Angeles, CA, Sept. 15-20, 1996.

[2-4] A. Clapp, C. C. Landinger, and W. A. Thue, "Safety Considerations of Aerial Systems Using Insulating and Covered Wire and Cable," *Proceedings of the 1996 IEEE/PES Transmission and Distribution Conference*, 96CH35968, Los Angeles, CA, Sept. 15-20, 1996.